

Final Report

Origins of Coastal Uplift in San Diego and Orange Counties: Huge Blind
Thrusts or Aseismic Rift Shoulder?

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Karl Mueller
Department of Geological Sciences
University of Colorado, Boulder CO 80309
(303) 492-7336 2-2606 (fax)
Karl.Mueller@Colorado.edu

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Origin of Regional Uplift Across Southern California and Northern Baja California: Rift-Related Flexure of the Lithosphere

Grant Kier, Karl Mueller and Thomas Rockwell*

Department of Geological Sciences
University of Colorado
Boulder Colorado 80309-399

*Department of Geological Sciences
San Diego State University
San Diego, California 92182

Abstract

Regional uplift in southern California, USA and northern Baja California, Mexico results from flexure of the elastic lithosphere in response to the formation of the Gulf of California Rift basin. Structural interpretations of surface faults and seismic reflection, seismic refraction, gravity and heat flow data from the Gulf Extensional Province and surrounding region constrain models of mechanical unloading of broken and continuous elastic plates. Although broken plate flexure is insufficient to produce observed regional topography, continuous plate models predict topography across the Peninsular Ranges, Salton Trough and Chocolate Mountains reasonably well. Furthermore, the continuous plate models predict uplift on the Pacific Coast that is similar in magnitude, and spatially coincident with, a regional background uplift signal recorded in coastal marine terraces. Observed northwest-southeast variations in topography on both sides of the Gulf of California rift system are accounted for in a northern and southern model. On the western rift flank the models suggest that observed northwest to southeast variation in the high topography of the northern Peninsular Ranges results from southward thinning of the elastic lithosphere and increased basin width. The models suggest that the more narrow basin in the north results in uplift of the eastern rift flank, the Chocolate Mountains, whereas increased basin width in the south results in a notably absent rift shoulder as observed in coastal Sonora, Mexico.

1. Introduction

Quaternary uplift of coastal southern California and northern Baja California has long been recognized by the presence of distinct flights of marine terraces along the Pacific coast (Arnold, 1903; Kennedy et al., 1982; Kern and Rockwell, 1992). The cause of uplift, however, has not been studied in detail, nor has it appeared significant until the recognition of active blind thrust faults in offshore regions of the southern California Borderland by Rivero et al., (2000). They attribute the observed coastal uplift to slip on a blind thrust system that includes one segment (the Oceanside detachment) extending down dip beneath the coastline, implying significant seismic hazard for coastal southern California and Baja California. In contrast, Johnson et al. (1976) and others (Muhs et al., 1992 and Orme, 1998) have argued that regionale uplift is due to aseismic tectonic or epirogenic processes.

In this paper, we explore whether, and to what extent, rifting in the Gulf of California and Salton Trough produces uplift of adjacent rift shoulders. We first test whether rifting of a thin elastic plate constrained by present geological and geophysical conditions in the Gulf of California can accurately predict observed topography. Second, we determine whether modeled rift shoulder uplift produces a total uplift signal along the Pacific coastline that is consistent with total observed uplift. Finally, we discuss the implications of our work on future research involving the use of marine terraces for uplift indicators in southern California and northern Baja California.

2. Geologic Setting and the Gulf of California Rift

The Peninsular Ranges of southern California and northern Baja California form the high-relief, western boundary of the northern Gulf of California and Salton Trough where oceanic transform and spreading ridges actively propagate into continental crust. This region, termed the Gulf Extensional Province [Gastil et al., 1975], is characterized

by low topography [Larsen and Reilinger, 1991] (Figure 1a.) produced by oblique extension in the trough that began ca. 4 to 6 Ma [Lachenbruch and Galanis, 1985].

Most geologic evidence suggests that the Gulf of California rift system resulted from an eastward jump of the easterly migrating Pacific-Farallon spreading ridge prior to its subduction beneath the North American plate near the end of the Middle Miocene at ca. 14 Ma [Atwater, 1970; Lyle and Ness, 1991]. It remains unclear, however, whether rifting began simultaneously along the entire extent of the new plate boundary, or if rifting propagated northward. Thinning and rifting of the continental crust over more recent spreading centers is oblique to the north-northeast rift trend [Axen and Fletcher, 1998] (Figure 1b.). In the southernmost Gulf of California sea-floor spreading began at ca. 8.3 Ma [Lyle and Ness, 1991], while spreading in the central gulf began at 7.1 Ma [Holt et al., 2000].

Localized Quaternary extension is produced in right stepping, right-lateral en echelon faults in the center of the Salton Trough [Elders et al., 1984] (Figure 1b). Igneous activity, a thin lithosphere (22 km) [Zhu and Kanamori, 2000], and a temperature gradient of $33.32^{\circ}\text{C km}^{-1}$ [Lachenbruch et al., 1985] all suggest that mantle upwelling is an active process beneath the region [Schubert and Garfunkel, 1984]. Topography, seismicity and crustal structure in the Salton Trough suggest its western margin is offset by active strike slip faults and that deep transtensional pull-apart basins are superposed on a broader extensional basin in the Laguna Salada region.

At the southern extent of the area we analyzed, the Gulf Extensional Province contains the Upper and Lower Delfin Basins, adjacent spreading centers in the Gulf of California [Lonsdale, 1989] (Figure 1b.). Spreading in this area began at ca 6.2 Ma [Oskin et al., in review] but may have been transferred from the Tiburón Basin to the Guaymas and Delfin Basins at approximately 3 Ma [Stock, 2000]. The entire length of the Gulf Extensional Province is truncated on the west by the Main Gulf Escarpment [Stock and Hodges, 1990].

The Main Gulf Escarpment is a discontinuous but linear system of east-side-down normal faults trending NNW for the entire length of the Baja Peninsula (Figures 1a, 1b). North of 30°N latitude, the Main Gulf escarpment is represented predominantly by the San Pedro Martir fault in the south and the Sierra Juarez fault system in the north [Gastil et al., 1975], separated by the active WNW-striking right-lateral Agua Blanca fault. The Sierra Juarez fault system is comprised of discontinuous, small ($<100\text{ m}$) to moderate ($100\text{-}500\text{ m}$) displacement faults [Axen, 1995, Stock and Hodges, 1990] (Figure 1b.). The San Pedro Martir fault has a steep, continuous footwall scarp with large ($\sim 5\text{ km}$) displacement [Axen, 1995] and late Quaternary scarps in alluvium (Brown, 1984). In the south, the San Pedro Martir fault segment of the Main Gulf Escarpment terminates abruptly at the Puertecitos Volcanic Province that is associated with the Motamí accommodation zone [Stock, 2000].

The Peninsular Ranges lie west of the Main Gulf Escarpment between $30^{\circ}\text{-}34^{\circ}\text{N}$ (Figure 1a). The mountains rise steeply along the escarpment to a maximum height of 3095 m with elevations gradually decreasing westward along a concave-upward slope [Lee et al., 1996]. Maximum elevations along the crest of the range vary between 1500 and 3000m; average elevations are lower to the north and increase toward the south. The Sierra San Pedro Martir terminates abruptly to the south at the Puertecitos Volcanic Province (Figure 1b). The Peninsular Ranges are comprised primarily of Mesozoic

batholiths intruded in an island arc regime. Emplacement of the batholiths ended at ca. 90 Ma, prior to their being deeply eroded and covered by Eocene conglomerates above a low-relief nonconformity [Gastil, 1975]. This ancient erosion surface, or basement-cover contact, is preserved in many locations along the Peninsular Range between the range crest and the Pacific coast. Where it is preserved, the erosion surface dips gently toward the Pacific coast and is mapped as high as 1830 m approximately 60 km east of the Pacific coast at N32°50' (Gastil, 1961).

3. Marine Terrace Uplift along the Pacific Coast

The Pacific coast west of the Peninsular Ranges mountains, from 30-33°N, is characterized by flights of marine terraces that imply continuous uplift during the late Quaternary. Many of the most prominent terrace platforms are present in areas where faults influence and control coastal structure and geomorphology, such as in the Palos Verdes peninsula [Woodring et al., 1948; Muhs et al., 1992], San Joaquin Hills [Grant et al., 1999], Mt Soledad region of San Diego [Kern and Rockwell, 1992], and Punta Banda region [Rockwell et al., 1989] (Figure 2). Shortening above blind thrusts, or in restraining bends of strike-slip faults, produces local uplift in these areas that is superposed on regional uplift occurring at a lower rate. It is this regional, or background, uplift signal that is the focus of this study.

In summary, the late Quaternary background uplift rate is well-known for much of southern California and northern Baja California and averages about 0.13-0.14 mm/yr from south of the San Joaquin Hills in Los Angeles southward to the Ensenada region. South of the Agua Blanca fault, the uplift rate is similarly low at about 0.13 mm/yr to 30° north latitude. Uplift of terraces decreases to zero southward at 28.6° north latitude except where they are locally deformed along strike slip faults. The highest observed terrace in southern California is the Rifle Range terrace that now stands at 155 m above sea level [Kern and Rockwell, 1992] in San Diego County.

In San Diego County, the highest marine terraces preserved inland from the coast are incised into late Pliocene and early Pleistocene strata of the San Diego formation, that were deposited in coastal estuarine environments. These sediments were deposited at a time when sea level was about 60 m above its present elevation [e.g. Dowsett and Cronan, 1990]. Given the present elevation of the San Diego Formation in the San Diego region (155 m above present sea level), we argue these strata have undergone about 95 m of uplift since they were deposited in the middle to late Pliocene.

3. Rift Shoulders

Rift flank mountains or “rift shoulders” are common topographic features along extensional basins and continental rift margins throughout the world. Examples include the Transantarctic Mountains in Antarctica [Stern and ten Brink, 1989], the Rhine Graben [Weissel and Karner, 1989], the Rio Graben in Greece [Poulimenos and Doutsos, 1997], and the East African Rift [Bott, 1992, Bott and Stern 1992, Zeyen et al., 1997]. Rift shoulders form where normal faults accommodate thinning in a divergent regime. As the hangingwall subsides, forming a rift basin, the footwall flanking the basin is uplifted (Figure 3). Maximum subsidence occurs over low-density material along the rift axis, while uplift of rift shoulders occurs some distance away from the low-density material depending on the rigidity of the lithosphere [Chery et al., 1992]. Rift shoulders range in

height from 1000-5000 m along continental rift systems and vary as a function of both the uplift force and the rigidity of the lithosphere [Chery et al., 1992]. Rift shoulders are typically asymmetrical with a steep escarpment facing the rift and gradually decreasing elevation along a concave-up slope away from the rift [Stern and ten Brink, 1989].

As early as 1976 topography observed across the Peninsular Ranges and Salton Trough was qualitatively compared to other rift shoulders around the world [Johnson et al., 1976]. The maximum elevations along the range crest adjacent to the western edge of the Salton Trough vary from ~3000 in the south to ~1500 m in the north. These regions of high relief lie in the footwalls of the Sierra San Pedro Martir and Sierra Juarez fault systems and form distinct rift segments.

Evidence for an extensional origin of the Salton Trough include the overall asymmetric geometry of the basin that underlies it (i.e. a half-graben), low-angle normal faults exposed along its western margin north of the International Border (Axen, 1995) and active high-angle normal faults in Baja California. These observations suggest the Salton Trough is underlain by an east-rooted extensional fault system that is overprinted by coeval or younger strike slip faults that trend oblique to the main rift axis. The following section demonstrates how observed topography between the Pacific coastline and the western edge of the Salton Trough compares quantitatively with rift shoulders produced along segmented extensional fault systems.

4. Modeling of Lithospheric Flexure - Methods:

Lithospheric flexure models treat part of the earth's lithosphere as a thin elastic plate over a fluid [Turcott and Schubert, 1982]. Flexure is most often observed where localized loads, such as ice caps or seamounts, depress the Earth's lithosphere far beyond the boundaries of the load. However, forces such as low density mantle anomalies [Angevine and Flanagan, 1989], erosion [Poulimenos and Doutsos, 1997], and normal faulting [Weissel and Karner, 1989] can also cause negative loads that result in upward flexure of the lithosphere. How much or little the lithosphere bends in response to any load is determined by the flexural rigidity of the lithosphere, D , a function of lithospheric elastic thickness (T_e), as

$$(1) \quad D = ET_e^3/12(1-\sigma^2)$$

where E is Young's modulus and σ is Poisson's ratio. Previous definitions of elastic thickness depend on the depth to an isotherm. Generally the adopted isotherm ranges between 300° and 600° C [Watts, 2001]. To maintain consistency with the model we employ, we define the elastic thickness as the depth to the 450° C isotherm after Weissel and Karner (1989). The general equation for modeling lithospheric flexure is

$$(2) \quad D \nabla^4 W(x) + \Delta \rho g W(x) = P$$

where $W(x)$ is vertical displacement, g is acceleration due to gravity, $\Delta \rho$ is the density contrast above and below the plate, and P is the load driving the displacement [Nadai, 1963].

We employ a rift-related flexural model whereby slip along a normal fault and hangingwall collapse create a rift basin infilled by sediment to sea level (Figure 3). The

isostatic response to basin development generates a negative load on the elastic lithosphere resulting in uplift of the elastic plate (Figure 4) [Weissel and Karner, 1989]. The initial geometry of the basin, and therefore the magnitude and distribution of the load, are determined by the heave (e_0) and geometry of the detachment fault. Our model uses the methods of Weissel and Karner, 1989 for a listric detachment fault that soles into the base of the crust. Although master extensional fault geometries for the Salton Trough are poorly constrained, we use an east-rooted detachment geometry for our flexural model that satisfies observations of crustal structure, basin asymmetry and thickness of Neogene sedimentary infill in this region. The strike-slip component of the transtensional tectonic regime is ignored for simplification of the model.

Values used in our model are listed in Table 2 along with the sources used to constrain each parameter. Predicted topographic deflection from this model is sensitive to small changes in T_e (Figure 5) and e_0 but is relatively insensitive to small (km scale) changes in the depth at which the detachment ultimately flattens [Weissel and Karner, 1989, Ebinger et al., 1991].

The fit of the model to observed topography is judged by several criteria. First, we test whether the flexural wavelength of the model, or distance between the Pacific coast and the edge of the rift, is similar to that which is observed in topography. Second, the magnitude of deflection (i.e. elevation) should match that of the observed topography. This approach is limited because pre-rift topography, or paleo elevation is not well constrained. We argue however, that the northern Baja California Peninsula must have been relatively low in elevation prior to extension because distinctive rhyolitic clasts deposited in the Eocene Stadium and Poway conglomerates exposed throughout San Diego County, and were sourced from volcanic centers in northwestern Sonora [Kies and Abbot, 1983]. Given appropriate reconstruction across strike slip faults of the plate boundary, these deposits must have been shed westward across the Baja Peninsula in Eocene time, prior to the development of significant relief. In addition, the drainage channel network developed on the Laguna Mountain, Sierra Juarez and Sierra San Pedro Martir rift shoulder segments is not deeply incised. We interpret this as additional evidence for low relief prior to recent uplift, otherwise, channels cut into batholithic rocks would be much more deeply incised to local base levels that must have approached mean sea level given the narrow width of the Peninsula.

Based on this evidence, we assume that the region was relatively flat and low in elevation (possibly sloping very gently toward the Pacific coast), and therefore initial topography in our model is defined as a flat surface at zero elevation. The goodness of fit between modeled and actual elevation is defined by comparing flank height and wavelength in the model with observed topography, as well as the observed basin geometry with depth of fill in the Salton Trough.

Existing structural geology, gravity, seismic refraction and heat flow data discussed above constrain our flexural models of the Peninsular Ranges (Table 2). We test a northern model across the Sierra Juarez (Model N3) and a southern model (Model S2) across the Sierra San Pedro Martir (see location of models on Figure 1). Predicted topography from the northern model is compared to a 50 km wide swath of average topography across the Peninsular Ranges, Salton Trough and Chocolate Mountains near the US-Mexico border. The northern topographic swath is located along a transect that includes the best constrained subsurface basin structure and gravity data for our model.

Observed topographic profiles are extracted from the ETOPO5 data set using the software package ENVI[®] 3.1, which provides better than adequate resolution for this study. The depth and shape of the asymmetric extensional basin underlying the Salton Trough in the northern model is constrained by seismic refraction data [e.g. Fuis et al., 1984].

We assume that the 450° C isotherm may be a reasonable approximation for T_e across our study area (Watts, 2001). The 450° C isotherm in our model is constrained by published heat flow data in the region [Lachenbruch et al., 19**]. As defined by the 450° C isotherm, T_e is approximately half as thick (13 km) under the rift basin as under the adjacent ranges (24 km). Since predicted topography is sensitive to elastic thickness we also test a range of constant values for T_e in order to judge its effect on model sensitivity (Figure 5).

The listric fault in our study is described by the equation

$$(3) \quad t_d = t_c * [1 - (\exp[-1 * k_d * x])]$$

where t_d is the depth to the detachment, t_c is the depth at which the fault flattens and k_d describes the curvature of the fault (Weissel and Karner, 1989). In our model the dip of the fault at the surface is 55°. Predicted topography is not greatly effected by the depth at which the fault flattens, but basin shape is sensitive to fault dip over the length of e_o . The thickness of basin infill as well as depth and shape of the underlying basement rock across the model are constrained with published seismic refraction data. The density of sediment infilling the basin is assumed to be 2650 g/cm³ throughout (Fuis et al., 1984, Weissel and Karner, 1989). The southern model differs from the northern model with respect to a decreased elastic thickness under the Peninsular Ranges and a thinner crust under the basin as suggested by Lewis et al., [2001] (Table 2).

Previous rift shoulder analyses have included the effect of erosion in rift models and its role in producing negative loads [Stern and ten Brink, 1989]. We consider this effect by allowing part of the excess mass beyond the observed Peninsular Ranges summits to erode into the basin. This effect is considered due to the instability of the steep fault at the surface and results from converting a small amount of crustal density material to sediment density and moving the mass from the rift shoulder on the footwall of the detachment into the adjacent basin. The small density conversion and short transport distance of this material with respect to the flexural wavelength result in negligible vertical deformation of the model. We consider the negative load due to fluvial erosion using an average net yield of 1000 kg yr⁻¹ ha⁻¹ of suspended material measured in river networks in the Peninsular Range Province by Inman and Jenkins [1999]. However, the resulting stress due to this rate of erosion is insufficient to produce significant deformation given the elastic thickness in the models. Given this and the shallow incision of river channels into the rift shoulder segments discussed in an earlier section, we therefore ignore uplift that results from fluvial erosion processes across the Peninsular Ranges.

5. Model Results:

The northern model predicts a maximum basin depth of 5.3 km and a flexural wavelength that closely matches the observed topography across the northern Peninsular

Ranges (Figure 4). Also, the model predicts a smaller uplifted flank east of the basin that is coincident with an elongate, narrow range of uplifted basement rock, the Chocolate Mountains. The geometry of the ground surface in the hangingwall broadly matches the basement-sediment contact interpreted on seismic refraction data (Fuis et al., 1984). The northern model predicts total uplift within a point 5 km east and west of the Pacific coast to range from 70 to 170 m.

The southern model predicts a similar maximum basin depth to the northern model of 5.3 km. In contrast to the northern model, a more gently sloping hangingwall surface is required across the basin, resulting in no significant eastern flank uplift (Figure 6). A slightly thinner elastic thickness under the western footwall flank results in slightly greater uplift (~2 km vs. 1.3 km) and smaller flexural wavelength (366 km vs. 406 km) than the northern model. This north to south difference in model prediction matches a similar trend in the observed topography in the northern and southern Peninsular Ranges. The southern model predicts uplift within 10 km of the Pacific coast to range from 60 to 170 m.

6. Discussion

A model of rift extension and mechanical unloading of the lithosphere predicts topography that matches the observed basin and flank topography across the northern and southern Peninsular Ranges. Perhaps the most noteworthy differences in topography between the Sierra San Pedro Martir and the Sierra Juarez are maximum elevations of the ranges and the distance over which the maximum elevations are achieved. The Sierra Juarez rises ~ 1.3 km over a distance over ~80 km. In contrast, the SSPM rises ~2km over ~ 60 km. This difference in topography is reproduced in our modeled topography by reducing the elastic thickness beneath the footwall rift flank by 3 km in the southern model, thereby reducing the flexural wavelength by 50 km. We interpret a decrease in elastic thickness as the cause of the increased relief observed in the Sierra San Pedro Martir.

Another important difference between the northern and southern models is the basin width. The more narrow basin width in the northern model results in uplift on the eastern rift basin flank. In the northern model this uplift signal is coincident with and similar in relief to the Chocolate Mountains. The uplift of this flank does not exist in the southern model since the eastern edge of the basin reaches the surface beyond (east of) the flexural signal. We interpret the Chocolate Mountains as the eastern, uplifted rift flank of the northern Gulf of California rift system.

In both models uplift is predicted along the Pacific Coast. Total observed uplift at the Pacific coast since deposition of nearshore deposits of the the middle to late Pliocene San Diego Formation is on the order of 100 m [Dowsett and Cronan, 1990]. This total observed uplift is within the range of predicted total uplift at the coast resulting from both flexure models and can be interpreted to indicate flexure-related uplift occurred primarily after deposition of the late Pliocene at this latitude. Further, the north to south extent of marine terraces uplifted at a low background rate since the marine Stage 5e sea level highstand is coincident with high topography in the Laguna Mountains, Sierra Juarez and Sierra San Pedro Martir (Figure 2). South of 30.5° N latitude, the Marine Stage 5e terrace has not been uplifted above sea level and relief along the western edge of the Gulf of California drops abruptly to nearly sea level.

We interpret the sudden decrease in relief and uplifted terraces at 30.5° N latitude as a transition from crust that maintains finite rigidity in the north to crust that has lost rigidity in the south. Our conceptual model suggests that topography south of 30.5° N latitude may once have had an elastic thickness that supported high topography during extension (as our model suggests is presently true in the north). As the elastic thickness reduced (i.e. the depth to the 450° C isotherm decreased) in the south due to high heat along the rift the rigidity of the lithosphere was insufficient to support the load. As a result of this decreased rigidity the southern rift flank would either remain stable or subside as the rift continued to evolve.

7. Conclusion

Rift related flexure of the lithosphere produces uplift of the northern Peninsular Range Province in southern California and northern Baja California. Modeled mechanical unloading of the lithosphere and the associated flexural response predict topography that closely matches the observed elevation of rift shoulder segments across both the northern and southern Peninsular Ranges. A decreased elastic thickness in the model is used to account for an observed increase in elevation and decrease in wavelength of the Sierra San Pedro Martir in comparison to the Sierra Jaurez. Uplift of both models closely matches long wavelength east-west topography across the Peninsular Ranges. We suggest that future studies of uplift along the Pacific coast for seismic hazard analysis should also consider uplift due to rift related flexure.

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Table 1. Locations and elevations of marine terraces measured along the Pacific coastline. Location shown on Figure 2. Table divided for format.

Table 1.						
Terrace Locality	North	West	5a Elev.	5e Elev.	Pliocene	Uplift Rate
	Lat (°)	Long (°)	(m)	(m)	Elev	(mm/yr)
San Joaquin Hills			19	32		0.21-0.24
Oceanside	33.35	117.52	9	22		0.13
No. San Diego County	33.17	117.35	9	22		0.13
San Diego (out of fault zone)	32.91	117.24	9	22		0.13
Mt. Soledad	32.85	117.27	14			0.18
Pt. Loma	32.69	117.25	9-10	22		0.13
Tijuana Playa	32.5	117.15		≥20		≥0.12
Rosarito Beach	32.3	117.08		23		0.14
Punta Descanso	32.24	117.03		23		0.14
Alisitos/La Fonda	32.1	116.91		9-10		0.03
Ensenada	31.85	116.65		20?		~0.12
Punta Banda	31.73	116.77		27-43		0.16-0.29
So. Maximinos	31.65	116.7		29-30		0.18
Punta Santo Tomas	31.54	116.72	8-9			0.13
Punta China			8-9			0.13
Punta San Jose	31.45	116.64				
Punta Cabras	31.3	116.48	6	17		0.08-0.10
Bahia San Quintin	30.4	115.95				
Punta Baja	29.94	115.81	>4-5 (8-10)	10?		0.03-0.14
Isla de Guadalupe	29°			6		0
Punta Chivato	27.1	111.95	n.o.		n.o.	
Mulege	26.9	112	n.o.	12		0.04-0.05
Punta Rosalilita	28.66	114.27	n.o.	6	+/-20	0
San Ysidro Fault Zone						
Turtle Bay, Vizcaino Pen.	27.67	114.88	12	24-27	n.o.	0.15-0.16
Cabo San Luca	22.85	109.9	n.o.	6	n.o.	0

Table 1.	
Terrace Locality	References
San Joaquin Hills	Grant et al., 1999
Oceanside	Kern and Rockwell, 1992
No. San Diego County	Kern and Rockwell, 1992
San Diego (out of fault zone)	Kern and Rockwell, 1992
Mt. Soledad	Kern and Rockwell, 1992
Pt. Loma	Kern and Rockwell, 1992; Kern and Ku, 1977; Muhs et al., 1992
Tijuana Playa	Valentine and Rowland, 1969
Rosarito Beach	Valentine, 1957, Valentine and Rowland, 1969

Punta Descanso	Valentine, 1957
Alisitos/La Fonda	Kennedy et al., 1986; (SLA in fault zone)
Ensenada	Kennedy, Rockwell, unpub. data
Punta Banda	Rockwell et al., 1989
So. Maximinos	Rockwell et al., 1989, Kennedy et al., 1986
Punta Santo Tomas	Emerson, 1956
Punta China	Emerson, 1956;
Punta San Jose	Emerson, 1956
Punta Cabras	Addicott and Emerson, 1959; Kennedy, pers. comm.
Bahia San Quintin	Emerson, 1956;
Punta Baja	Emerson and Addicott, 1958; Ortlieb et al., 1984, Kennedy, unpub. Data
Isla de Guadalupe	Lindberg et al., 1980
Punta Chivato	Kennedy, Rockwell, unpub. Data
Mulege	Ashby et al., 1987;
Punta Rosalilita	Emerson and Hertlein, 1960; Kennedy, unpub. Data
San Ysidro Fault Zone	
Turtle Bay, Vizcaino Pen.	Emerson, 1980; Emerson et al., 1981, Ortlieb et al., 1984
Cabo San Luca	Muhs et al., 1992

Table 2. Physical constants and rheological values used in flexural analysis.

Table 2.			
Parameter	north model	south model	Definition
x	m	m	horizontal coordinate
t _d	Eq 3	Eq 3	depth of detachment
t _c	13 km	10 km	crustal thickness
a	40 km	40 km	lithospheric thickness at the time of extension
e _o	5 km	5 km	heave on detachment fault
δ(x)	varies with x	varies with x	pure shear in footwall
β(x)	varies with x	varies with x	pure shear in hangingwall
ps	2650 kg/m ³	2650 dg/m ³	density of sediment infill
pc	2800 kg/m ³	2800 kg/m ³	density of crust at 0°C
pm	3300 kg/m ³	3300 kg/m ³	density of mantle at 0°C
pa	3179 kg/m ³	3179 kg/m ³	density of asthenosphere
T _m	1333°C	1333°C	temperature at the base of the lithosphere
α	3.4 X 10 ⁻⁵ /C°	3.4 X 10 ⁻⁵ /C°	coefficient of thermal expansion
k	8.0 X 10 ⁻⁷ m ² /s	8.0 X 10 ⁻⁷ m ² /s	thermal diffusivity
D(x)	Eq 1	Eq 1	flexural rigidity
E	10 ¹¹ N/m ²	10 ¹¹ N/m ²	Young's modulus
v	0.25	0.25	Poissan's ratio
Te	varies with x	varies with x	effective elastic thickness of the lithosphere
g	9.8 m/s ²	9.8 m/s ²	gravitational acceleration

Figure 1

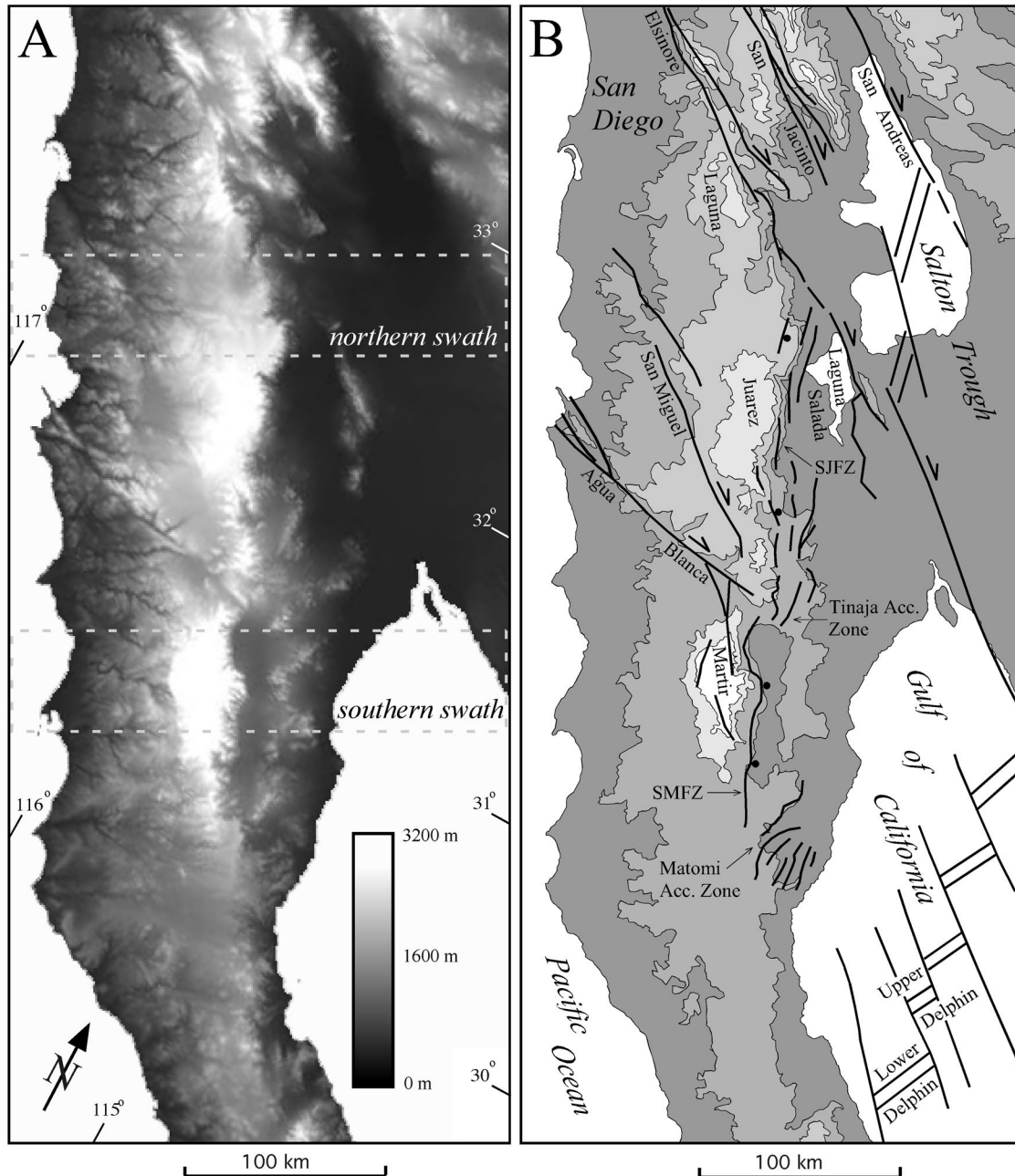


Figure 1A. Digital elevation model (DEM) of the study area in southern California and northern Baja California. Dotted boxes represent locations of topographic swath averages and regions of northern and southern models. **Figure 1B.** Simplified geologic map of the same region with 500 m contour intervals. The Matomí (MA) and Sierra La Tinaja (SLT) accommodation zones are bordered with thick grey lines. The location of flexural Models N3 and S2 are represented by thick black lines. The Salton Trough is the northernmost part of the Gulf Extensional Province. Upper (UD) and Lower (LD) Delphin Basins represent the southernmost extent of the study area. The Main Gulf Escarpment is marked by the San Pedro Martir Fault (SPMF) south of the SLT while the

Sierra Juarez Fault System (SJFS) defines the escarpment north of the SLT. Topography in the Peninsular Ranges slopes gently towards the Pacific Ocean from highest elevations in the Sierra San Pedro Martir (SSPM) and the Sierra Juarez (SJ) which are located adjacent to faults of the Escarpment.

Figure 2

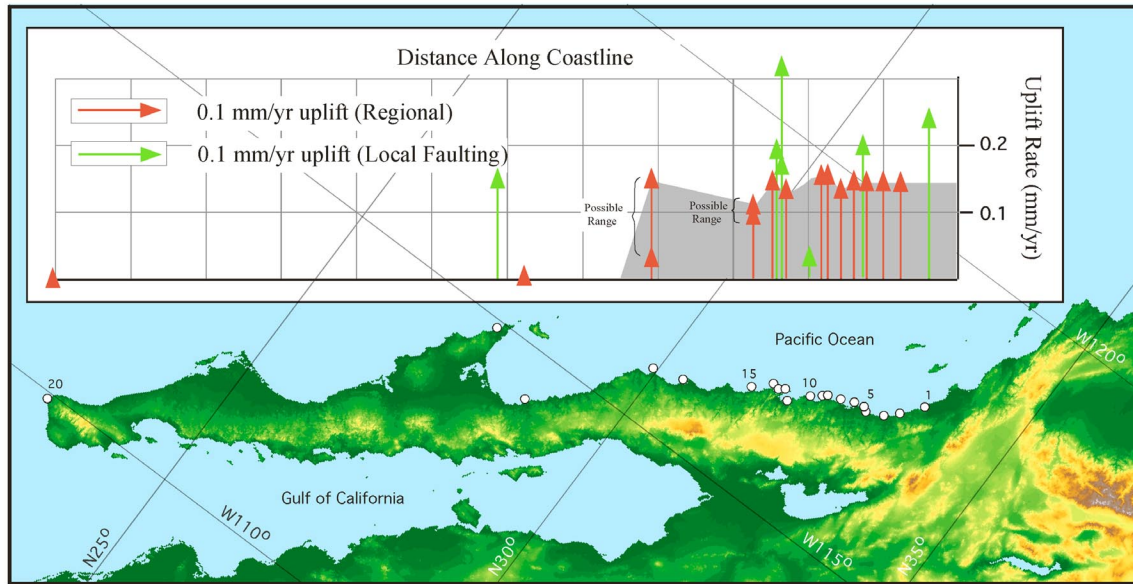


Figure 2. DEM of Peninsular Ranges with uplift vectors along the Pacific coastline as defined by Marine Stage 5a and 5e marine terraces. Data from Ortleib [1991] and unpublished data of T. Rockwell. Base of arrow denote location of measurement at coastline. Sites of measurements listed in Table 1 marked at intervals of 5, 10, 15 and 20, measured from north to south. Uplift rates recorded at 120 ka (Stage 5e terrace) and 80 ka (Stage 5a terrace) indicate that rates are lower south of the SLT accommodation zone and higher north of of the accommodation zone. Grey shading illustrates area of regional uplift related to rift shoulder development. Note correlation between southern terminus of regional uplift and morphology of rift shoulder which terminates along the same latitude at the southern end of the Sierra San Pedro Martir.

Figure 3.

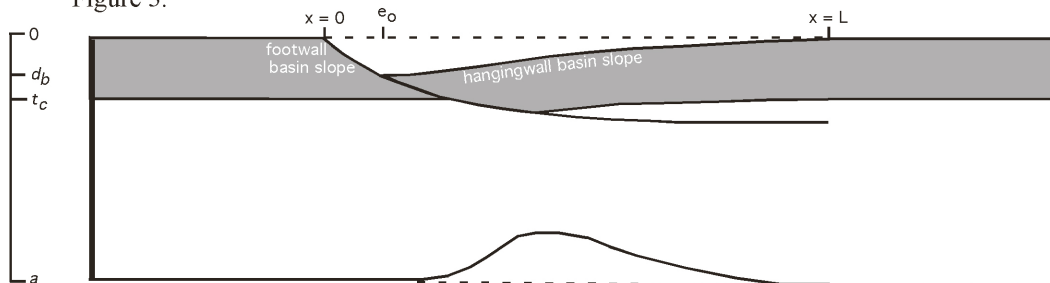


Figure 3. Cartoon of kinematic extension of the lithosphere (after Weissel and Karner, 1989). Slip along detachment fault results in rift basin. Basin geometry, including footwall basin slope, hangingwall basin slope, and maximum basin depth (d_b), is

determined by heave (e_0), listric fault geometry and total width of extension zone (L). Crustal thickness is (t_c). No lateral density variations exist below the depth of the unthinned lithosphere (a).

Figure 4

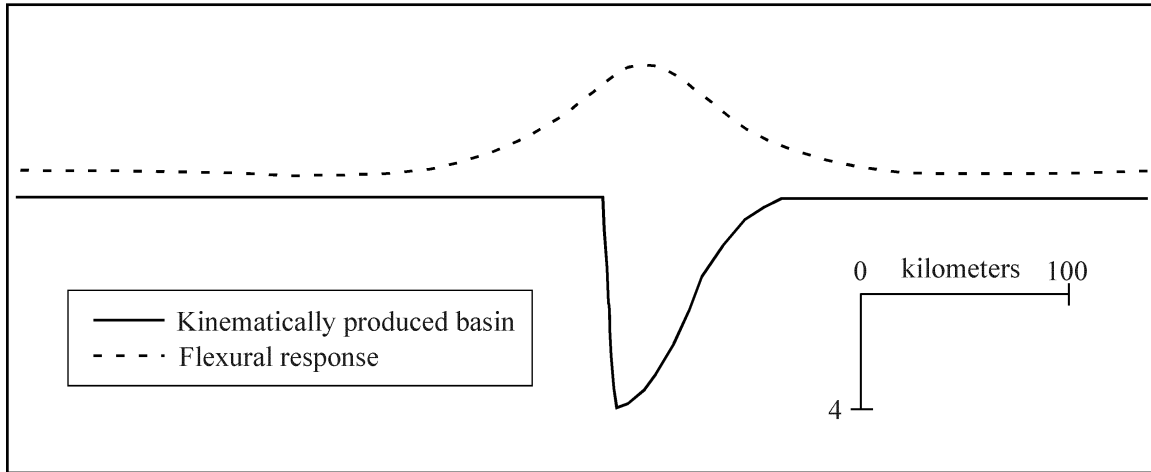


Figure 4. Generalized model illustrating depth and shape of a kinematically produced rift basin (solid line). Dotted line represents the elastic flexural response to the basin.

Figure 5

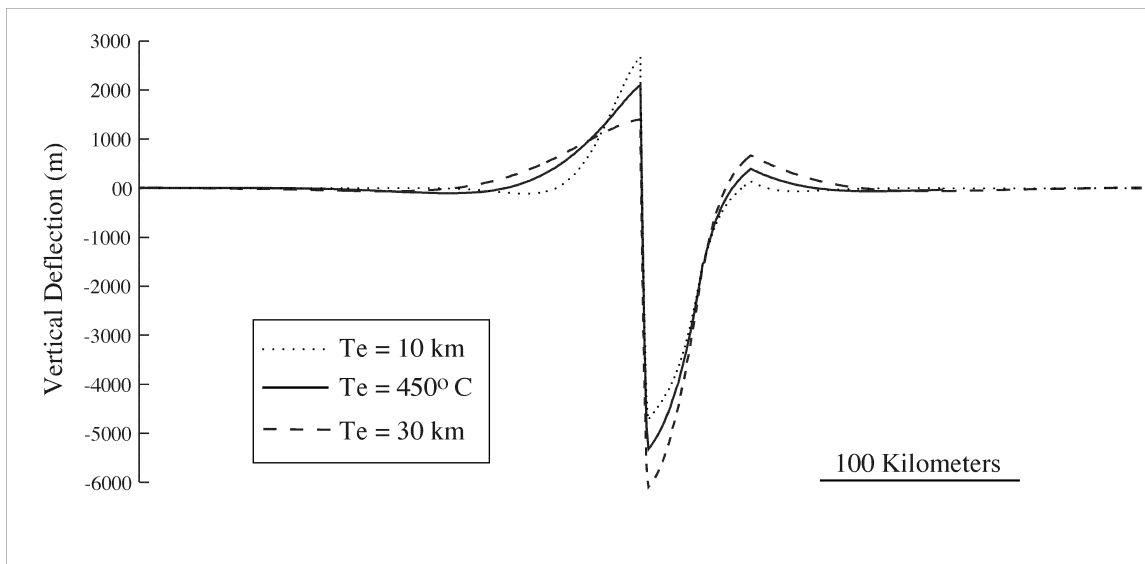


Figure 5. Model sensitivity to elastic thickness. All model parameters remain constant except elastic thickness. Dotted line represents a fixed 10 km elastic thickness throughout the model, dashed line represents a 30 km elastic thickness throughout the model and solid line represents an elastic thickness that varies laterally with the 450°C isotherm.

Figure 6.

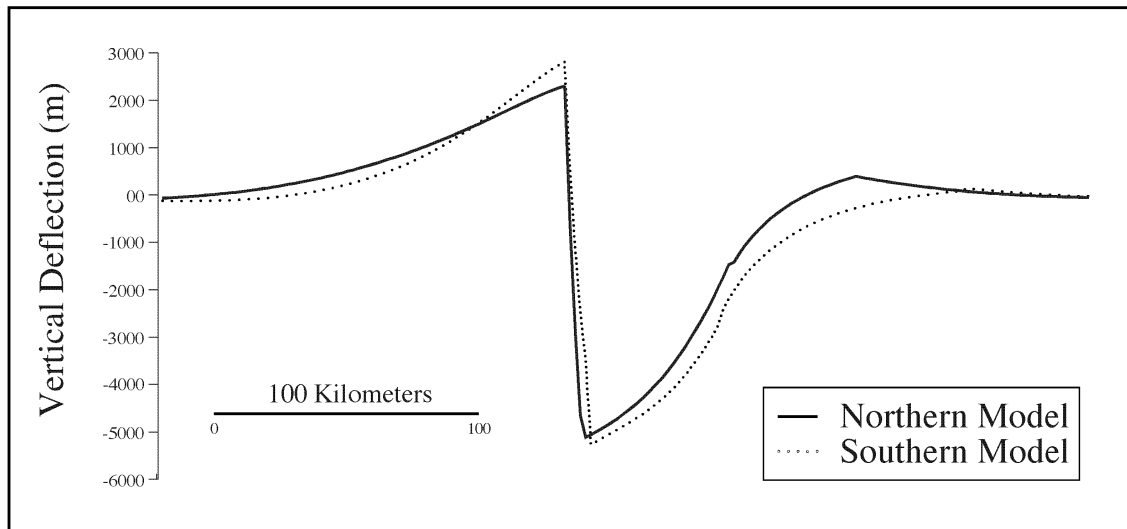


Figure 6. Comparison of the northern and southern models. Note the shorter flexural wavelength in the footwall rift flank for the southern model (dotted line), which results from slightly smaller elastic thickness. Also, in the southern model a wider and less steep hangingwall basin slope results in no uplifted rift flank in the hangingwall.

Figure 7

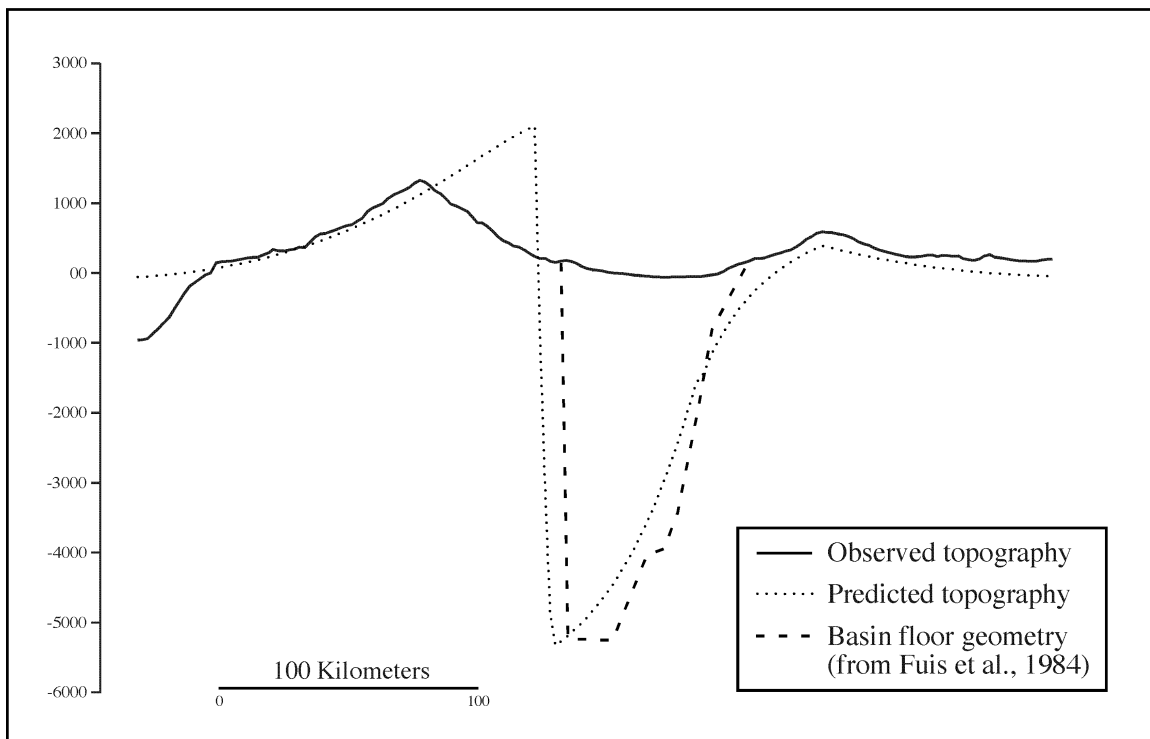


Figure 7. Northern model with predicted topography (dotted line) compared to observed topography (solid line) and interpreted basement-cover geometry (dashed line). Note the

similar flexural wavelength of the hangingwall flank. Predicted basin depth closely matches interpreted basin depth and broadly matches geometry. Also note the predicted uplift of a rift flank in the hangingwall that is coincident with the Chocolate Mountains.

Figure 8.

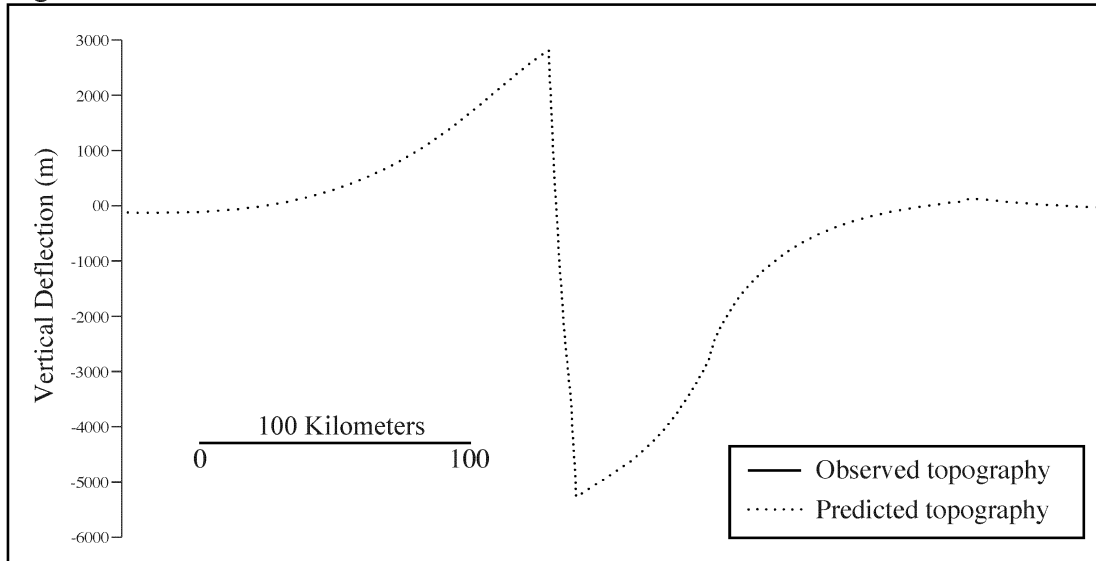


Figure 8. Southern model with predicted topography (dotted line) compared to observed topography (solid line). No interpreted basement was available for this location as for northern model. Note the similar flexural wavelength of the hangingwall flank. The wider basin results in no predicted uplift of the hangingwall rift flank, which is consistent with observed topography.

We assess the hazards of blind thrust faults in coastal Southern California and Northern Baja California with mapping of uplifted marine terraces along the Pacific coastline and development of models of lithospheric flexure of the Peninsular Ranges. Our results suggest regional uplift of young marine terrace deposits extends from Orange County to nearly the Vizcaino Peninsula and results from broad flexure of the lithosphere that increases westward to the edge of the Salton Trough and northern Gulf of California. We conclude that uplift along the Pacific coast is due to mantle derived bouyancy and not uplift above active blind thrusts.

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